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Kinematic couplings: A review of design principles and applications

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ABSTRACT

From the humble three-legged milking stool to a SEMI standard wafer pod location to numerous sub-micron fixturing applications in instruments and machines, exactly constrained mechanisms provide precision, robustness, and certainty of location and design. Kinematic couplings exactly constrain six degrees of freedom between two parts and hence closed-form equations can be written to describe the structural performance of the coupling. Hertz contact theory can also be used to design the contact interface so very high stiffness and load capacity can also be achieved. Potential applications such as mechanical/electrical couplings for batteries could enable electric vehicles to rapidly exchange battery packs.

1. Introduction

This paper focuses on the design of kinematic couplings and how they have been used in the past and how they can be used in the future. In addition to specific "how to" knowledge and examples for kinematic coupling design, the methodology of exact constraint design will be considered as a catalyst for mechanical design innovation.

Before precision manufacturing equipment and solid modeling became commonplace, design engineers often had to think very carefully how they would attain precision in products they were designing. This often led to the use of exact constraint design principles or careful application of elastic averaging to ensure that components could be assembled without causing undue stresses. However, as the quest for greater precision, reliability and lower cost become ever more apparent in a world of shrinking economies and global resources, design methodologies from the past could be a great asset for the future.

All mechanical things have a structure, and the structure is often made up of parts. Structural connections keep the parts permanently attached to each other. Structural interfaces allow parts to be easily attached and detached. Both cases require the design engineer to think in terms of springs and degrees of freedom. Two critical steps in the analysis of a design are to identify the structural loop and to assess the compliance of elements along it. Next, the stresses on elements along the structural loop are evaluated to ensure, for example, that bearings do not become overstressed when parts are bolted together.

The design of connections and interfaces can be bracketed by kinematic design (exact constraint design) and elastically averaged design [1–3]. As shown in Figs. 1a and b, consider a three-legged chair and its interface with the ground. For a three-legged chair, leg length and compliance are nominally not critical. Three legs will always contact the ground. However, such a chair is more prone to tipping as the load must be applied within the bounds of a triangle. On the other hand, consider a five legged chair where each leg has modest compliance, such that when a person sits on it, all the legs deform a little bit and so all legs make contact with the ground. The chair is more expensive to design and manufacture, but loads can generally be applied anywhere within the polygon that bounds the contact points.

2. Exact constraint design

A structural interface is considered to be a repeatable mechanical connection capable of withstanding structural loads, and it can be routinely taken apart and put back together. This is in contrast to structural joints which are not intended to be routinely taken apart. A structural interface must therefore provide constraints to control all the intended degrees of freedom. According to the principle of *Exact Constraint Design* (ECD): *The number of points of constraint should be equal to the number of degrees of freedom to be constrained*. This is the minimum, although some interfaces may utilize more constraints in order to achieve higher load capacity, repeatability, and accuracy using the principle of *Elastic Averaging*.

Fig. 2 shows the relative repeatability of different types of connections, and the goal of the designer is to pick the lowest cost method for the desired performance. Often it is good enough to use low cost keyways or pinned connections. Because they would typically be over constrained if an attempt were made to create an exact fit, tolerances are set so there is always some room between

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components. This loose fit ensures that parts can be assembled, but the accuracy and repeatability that can be obtained is limited by the toleranced gaps. The alternative is to use spring pins or numerous elastic elements that accommodate misalignment and tolerances by elastic deformation. However, designing a system that is over constrained takes exceptional care to ensure that deformations do not occur that may overload sensitive components such as bearings. Thus if possible, a good strategy is to try and create an exactly constrained design.

ECD often concentrates loads at single points which can lead to a smaller region of stability (e.g., 3 legged chair); however, ECD does not always mean that systems have to be designed like three-legged chairs. Ponder the following: Can you support a plate at multiple points yet not get the “four legged chair with one short leg” syndrome? How do windshield wiper blades distribute the point force applied by the arm uniformly across the blade? The answer to both questions is to use a wiffle tree as can be seen on any windshield wiper blade. Exact constraint design can sometimes be visualized by imagining how support points need to be applied to uniquely define the position of a cube using a 3-2-1 fixturing philosophy illustrated in Fig. 3. Each of the support points can in fact be the center of stiffness of an array of points on a wiffle tree arm; however, eventually at the connection to ground, 3-2-1 points are established:

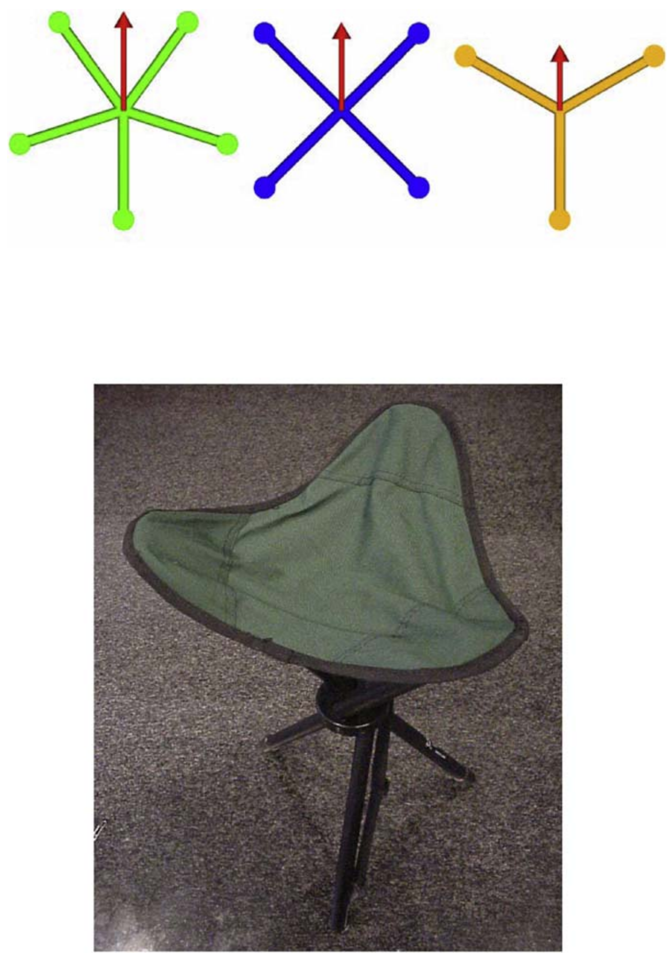

Fig. 1. (a) Support legs and stability arrows for chair legs ranging from elastically averaged to kinematic. (b) Kinematic design principles applied to create a collapsible camping stool as a modern variation of the classic three-legged milking stool.

1. One side is placed on three support points;
2. A second side is pushed up against two support points;
3. The first side slides across the three support points;
4. A third side is pushed against one support point;
5. The first and second side slide across their support points.

With the above, ideally, exact constraint is theoretically achieved, and for all practical purposes, it is when the loads are very light; however, when heavier loads are applied, which may be due to the weight of the object itself, point loads cause local deformations that act like additional orthogonal constraints. These point contact deformations and friction at them fully constrain the cube when it is first placed. As the cube is pushed against the other constraints, the point contact deformations and friction reduce the repeatability of the system. Hence the 3-2-1 fixturing method practically has repeatability on the order of 3–5 μm.

Both types of kinematic couplings are exact constraint designs to a point: the contact forces at each of the six points are high and micro indentations, although elastic typically, occur which serve to add in effect micro over constraints. The instant center of the couplings is known, and thus if there is uniform thermal

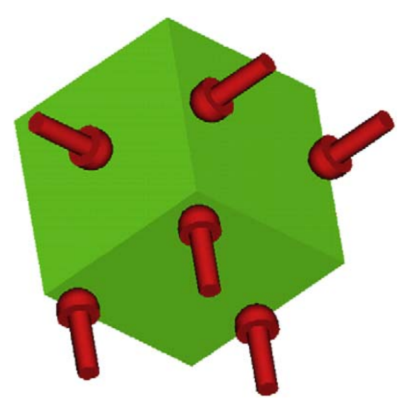

Fig. 3. 3-2-1 Fixturing principle applied to a cube.

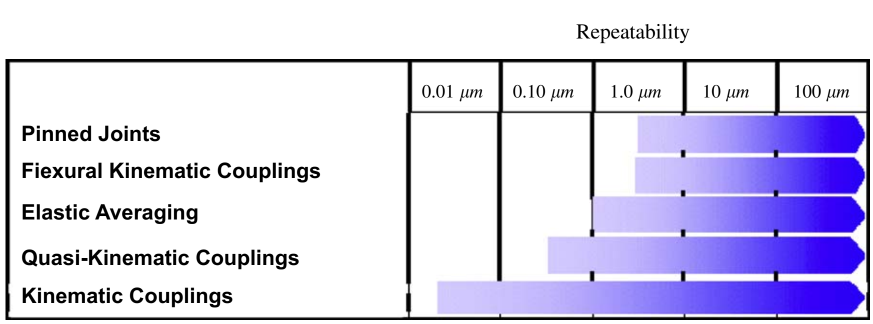

Fig. 2. Relative repeatability of different types of connections (Courtesy M. Culpepper).